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CLIMATE RESEARCH
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Rainfall and streamflows in the Greater Melbourne catchment area: variability and recent anomalies

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ABSTRACT: Observed rainfall and water availability is investigated across several catchments northeast of Melbourne using gridded rainfall data over the last 113 yr and reconstructed streamflow observations for the last 100 yr, focusing on the 1997–2009 record-breaking rainfall deficits, associated record-low streamflows and subsequent recovery from 2010 to 2012. These catchments provide drinking water for about 90% of the state of Victoria's population and hence are critical. The influence of large-scale tropical modes of climate variability affecting rainfall, and subsequently reservoir streamflows, are shown to be modulated by the orographic features marking this region. These remote large-scale tropical climate forcings have contributed strongly to recovery since 2010. However, across these catchments, the large-scale modes of natural variability do not explain the long-term deficit in streamflows in the last 15 yr. Annual streamflow in these wet catchments can skilfully be reconstructed month by month using catchment-wide observed rainfall. The year-to-year variability, decline during the last 30 yr and magnitude of the deficiency during the Millennium Drought are reasonably well captured but not fully accounted for by the linear combination of rainfall in the current month, the previous month and the previous 12 mo. Maximum temperature does not have a sizeable additional impact when added to the reconstruction, while the previous 12 mo of rainfall contribute to about 25% of the reconstruction's ability to capture many of these statistics.

KEY WORDS: Variability · Statistical reconstruction · Streamflow · Melbourne

1. INTRODUCTION

South-eastern Australia (SEA), defined as continental Australia south of 33.5° S and east of 135.5° E (Timbal 2009), had its lowest 13 yr rainfall between 1997 and 2009 compared to the entire 1900–2012 period. The 1997–2009 annual average of 512.4 mm was 12% below the 1900–2012 average annual of 582 mm (CSIRO 2012). We will use the terminology Millennium Drought (MD) as coined by Leblanc et al. (2011) to name that extremely low rainfall period occurring between 1997 and 2009 at the time of the transition to the new millennium. Two other low rainfall periods were seen in the instrumental record, which extends as far back as 1865 (Timbal & Fawcett 2013), one around the time of the federation of the Australian States (in 1901, Federation Drought) and the other during an extended period preceding and encompassing World War II (WWII Drought). The MD was unprecedented as it was more severe than either of these 2 previous droughts, and, in contrast to the previous droughts, the rainfall deficit in SEA happened during the cooler part of the annual cycle, from April to October, with the largest anomalies in autumn (Timbal 2009).

Timbal & Hendon (2011) have shown that the MD could not be accounted for by naturally occurring modes of variability generated within the tropics,

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such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). This is consistent with other calculations (Smith & Timbal 2012) and the fact that tropical modes of variability do not relate well with autumn rainfall in SEA (Timbal & Murphy 2007). Timbal et al. (2010) demonstrated that the rainfall deficit observed across SEA was related to an observed strengthening of the belt of high pressure — a feature evident at every longitude but, for this study, measured above the eastern part of the Australian continent following Drosdowsky (2005). This belt of high pressure, known as the sub-tropical ridge (STR), is a key controller of rainfall across southern Australia during the cool months of the year from April to October. In the 20th and early 21st century the ridge has been observed to evolve similarly to global average temperatures and to account for about two-thirds of the observed deficit across SEA during the MD (Timbal & Drosdowsky 2013).

The MD concluded in 2009; the spring/summer of 2010–2011 saw one of the strongest La Niña events on record combined with a negative IOD event and a positive Southern Annular Mode (SAM) event, i.e. all 3 key influences were in their wet phases in terms of expected rainfall impacts on SEA (CSIRO 2012). These conditions, coupled with the warmest sea-surface temperatures (SST) on record to the north of the Australian continent, contributed to making 2010–2011 Australia's wettest 2 yr period on record (Bureau of Meteorology 2012). While the extensive flooding of 2010–2011 was, by and large, consistent with natural variability (H. H. Hendon et al. unpubl.), it is possible that ongoing global warming contributed to the magnitude of the event through its impact on ocean temperatures (Evans & Boyer-Souchet 2012). The spring and summer of 2011–2012 saw the re-emergence of another (weaker) La Niña event, combined with a positive SAM event during early summer, but this time the Indian Ocean played a lesser role. Despite the La Niña events of 2010–2011 and 2011–2012, which resulted in above-average annual rainfall totals across the region, late autumn and winter rainfalls in 2011 continued to be below average, which is consistent with the trends associated with the observed evolution of the STR associated with the expansion of the Hadley circulation (Nguyen et al. 2013); in 2010–2012, the intensity of the STR averaged 0.3, 1.1 and 1.2 hPa above the 20th century average, respectively, in autumn, winter and spring.

The eastern area of Australia is dominated by the Great Dividing Range (GDR) — a range of mountains, up to 2000 m high, running approximately parallel to the coast from western Victoria in the south to mid-Queensland in the north, 200–300 km inland (Fig. 1a). The southern part of the GDR, within SEA, is where a large fraction of the run-off and streamflows into dams is generated. In this study we will focus on the central southern Victoria region (Fig. 1b) where Melbourne city and a large part of the northern half of the state of Victoria collect surface run-off into large dams north east of Melbourne. In the area of interest the GDR runs basically west–east; on the northern side of the GDR, Lake Eildon receives surface run-off from a large catchment (Fig. 1b); while on the south side lies the area managed by Melbourne Water. There is a significant north–south orientated range connecting to the GDR in a location named 'the Triangle', separating the Thomson catchment area in the east from the other major Melbourne Water catchments in the Yarra Basin to the west: Upper Yarra, O'Shannassy and Maroondah (comprising streamflow from Watts River and diversion from Graceburn Creek). These major water supply catchments all feed into the Yarra River, and we will referred to them as 'Yarra catchments'; note we do not include some minor Melbourne water supply catchments and tributaries within the Yarra Basin (e.g. Armstrong, Starvation and McMahon creeks). While the entire SEA has been extensively studied (CSIRO 2012), a specific study on these important catchments is lacking. It is therefore of interest to put the rainfall variability and, in particular, the magnitude of the MD across these major water supply catchments in perspective and compare them to the entire SEA region and the broader Murray-Darling Basin (MDB) which extends further north. Beside the importance of this region for water management and the provision of drinking water to Melbourne, all these catchments are inter-connected (water transfers are enabled from east to west and from north to south), offering interesting water supply operations and management opportunities and challenges for which improved understanding of variability and changes are valuable.

While average annual rainfall during the MD declined by an average of 12% across SEA, the impact on streamflows was even more extreme. Due to non-linear hydrologic processes, a magnified response of streamflows relative to rainfall (the 'elasticity factor') is expected (Chiew 2006) and are generally 2–3 times the magnitude of the respective decline seen in rainfall for the MDB region (Post & Moran 2013). However, non-stationarity was also observed during the MD as the elasticity response was much larger than during previous dry periods (Potter et al. 2010). This magnification of the streamflow response has been

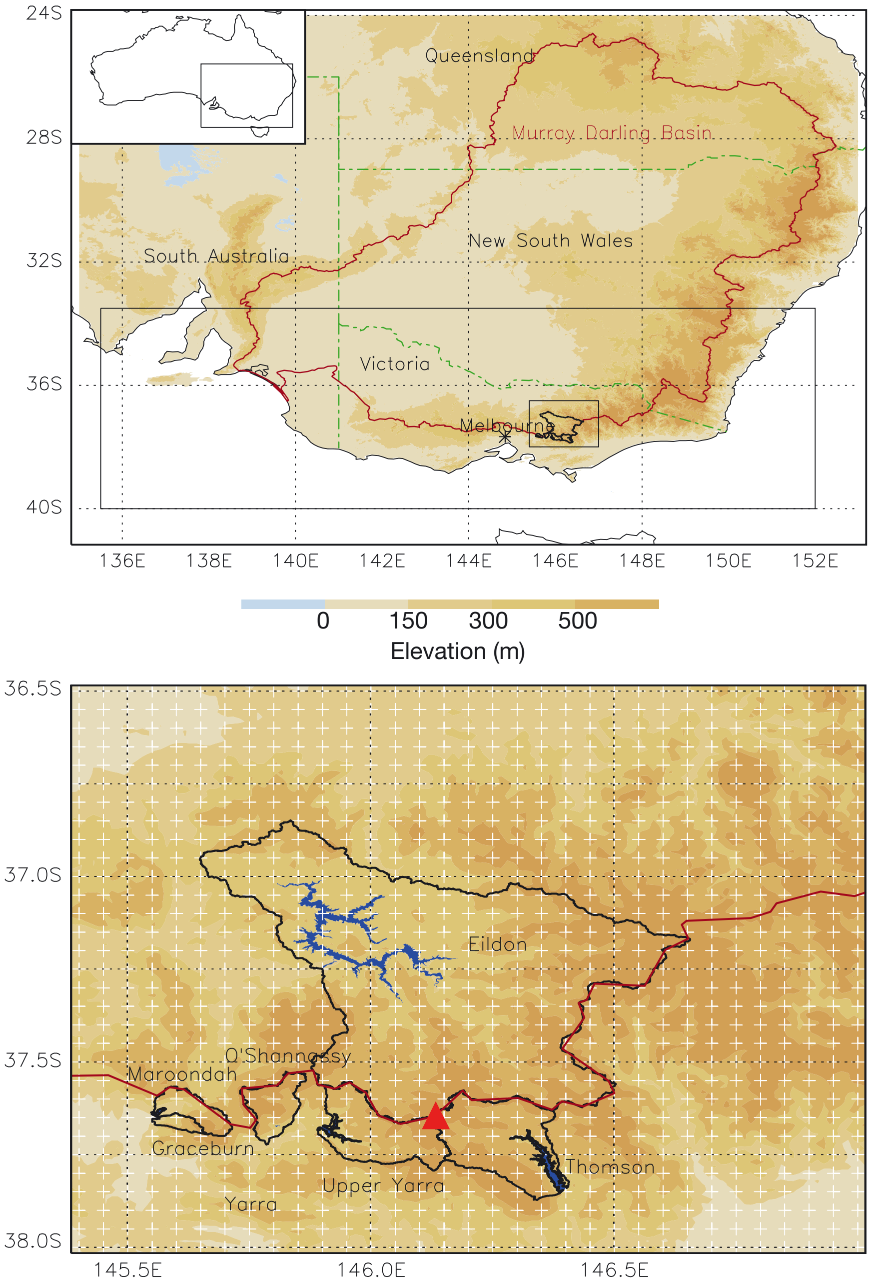

Fig. 1. South-eastern part of the Australian continent (upper panel) detailing the catchment boundaries for the Murray-Darling Basin (red line), the Eildon catchment and the main Melbourne Water catchment areas (enlarged in the lower panel). Key shows the height above sea level in metres; dark blue: reservoirs; white crosses: gridded observation resolution; red triangle: location of hill top called 'the triangle'

related to various factors, including the absence of wet years, increasing temperature and the change in seasonal rainfall patterns. All these factors may result in a substantial reduction in runoff generation during subsequent seasons. Some of these impacts are likely to be due to poorly understood hydrological processes (e.g. changes in ground water levels and connectivity with surface runoff). Some hydrological studies have focused on the Victorian and Melbourne Water catchments (Howe et al. 2005, Preston & Jones 2008) and many studies have focused on the hydrological implications of the MD (Kiem & Verdon-Kidd 2009, 2010, CSIRO 2010, 2012), but there has been a lack of study focusing on the impact of the MD and subsequent recovery for the catchments close to Melbourne, from which close to 90% of the State of Victoria's population rely on for town water supplies. Furthermore, in light of the inability of hydrological models to fully reproduce the impact of the MD on streamflow across the region and, in particular, the increase in the elasticity factor (CSIRO 2012), we decided to investigate an alternative approach and evaluate how well simple statistical relationships between rainfall and streamflow could capture the hydrological response to the MD in these important catchments east of Melbourne.

The aims of this research were as follows: (1) document the characteristics of the MD and subsequent recovery from 2010 to 2012 across the catchments east of Melbourne, with a focus on the importance of the marked orography across these various catchments which have different orientation (north of the GDR [Lake Eildon catchment] and south of the GDR [Melbourne Water major catchments], with a separation between the south-west-oriented catchment [the Yarra Basin catchments] and the south-east-oriented catchment [the Thomson catchment]); (2) for the same area evaluate how the large-scale drivers of rainfall differ across the various orientations of the catchments due to orography; and (3) evaluate how simple relationships between streamflows and rainfall can capture the specificities of these catchments and the marked variability across the observation record, in particular, in recent decades.

2. DATA AND METHODS

We used the Australian Bureau of Meteorology's (BoM) current operational high-resolution monthly rainfall analyses, generated as part of the Australian Water Availability Project (AWAP) (Jones et al. 2009). These analyses are based on a 0.05° × 0.05° resolution, or approximately 5 × 5 km. The methodology employed in these analyses is a hybrid type, merging 2-dimensional Barnes successive correction analyses (Jones & Weymouth 1997) of fractions of monthly mean rainfall and 3-dimensional thin-plate smoothing spline analyses (Hutchinson 1995) of climatological monthly rainfall.

The number of stations varies considerably during the period. For the purpose of understanding the changes in real stations feeding the gridded rainfall in the vicinity of the area of interest, records from stations have been combined, such that stations within 0.05° (approximately 5 km) of each other are grouped. Station record duration and location varies with time (Fig. 2). A station is considered active if there are data for ≥10 mo of the year and for at least 75% of the years during that time period. Focusing on 3 regions—the Eildon, Thomson and Yarra catchments—the time evolution of the number of stations reporting for each of these 3 areas is likely to influence the gridded rainfall, as the numbers of sta-

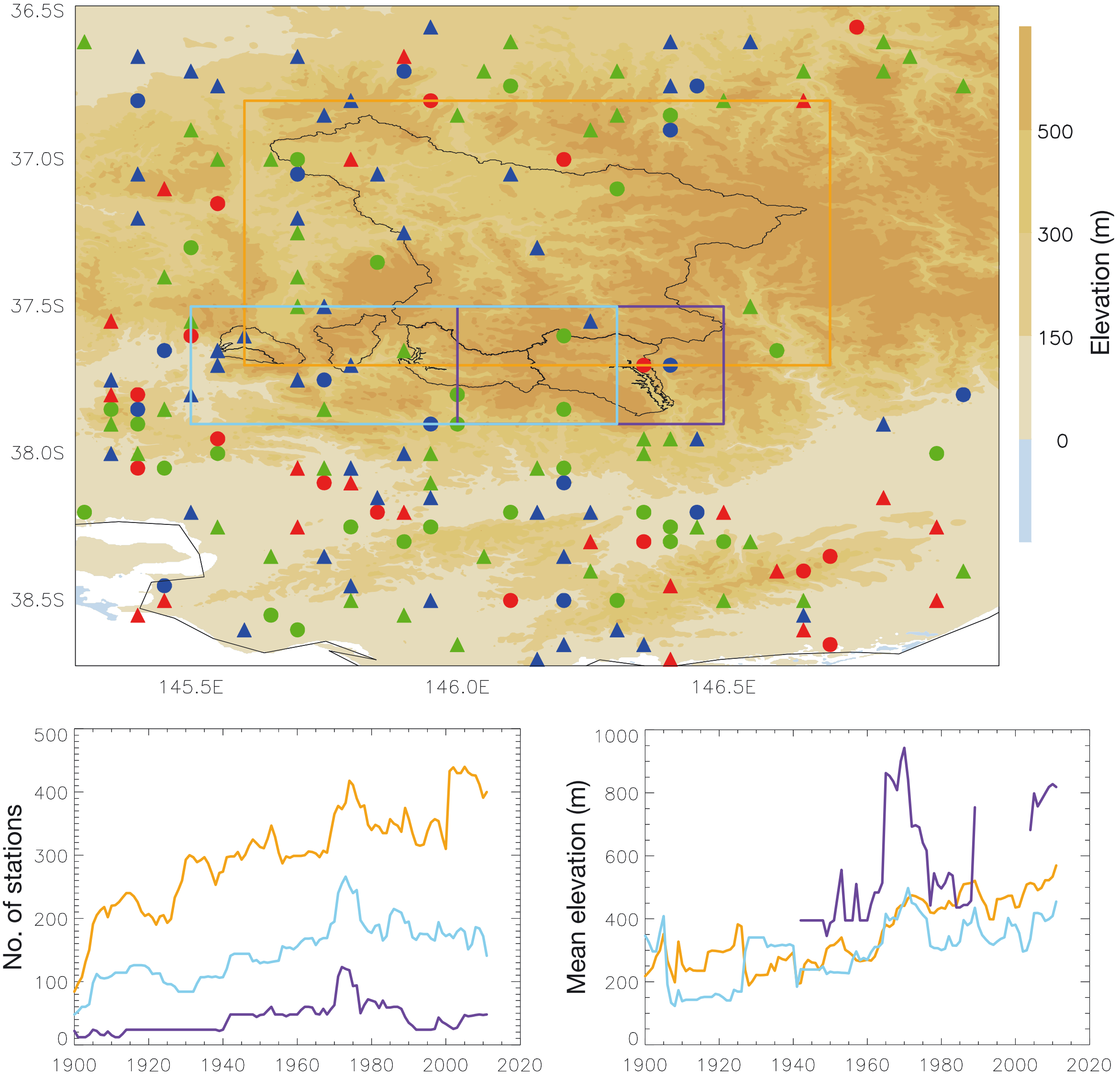

Fig. 2. Area of interest (upper panel) showing the locations of weather stations contributing to the gridded dataset. Stations in existence—red circles: 1900–1970; green circles: 1970–1980; blue circles: 1980–2010; red triangles: 1900–1980; green triangles: 1970–2010; blue triangles: 1900–2010. The coloured rectangles in the upper panel identify the 3 regions for which 2 statistics are provided in the lower panels: time-series of the number of stations (left panel) and the average altitude of stations (right panel)

tions steadily increased until the 1970s, before levelling off or decreasing (Fig. 2, lower left panel). Of particular concern is the coverage in the more mountainous parts of the catchment. The average altitude of stations within each of these regions shows that altitude has been increasing with time (Fig. 2, lower right panel). This non-stationarity is likely to have an effect on the time-series of the AWAP catchment average, as higher elevation stations tend to be wetter than low-elevation stations. It is therefore expected that the rainfall in the early record would likely to be lower due to station coverage. One would expect this effect to generate a spurious upward trend for rainfall across these catchments (the relevance of this data issue will be discussed further in Section 4).

The streamflow data at the Melbourne Water major water supply catchments (Yarra and Thomson catchments) were provided by Melbourne Water, and the data for the Eildon catchment were provided by the Department Environment and Primary Industries (DEPI). All streamflow data span the period 1913–2012. The monthly streamflow records at the Melbourne Water major harvesting reservoir sites are based on a reservoir mass-balance approach calculated using hydrological models and water level gauging records (taking into account the streamflow, outflow and change in storage). However, the earlier part of the monthly streamflow record prior to the construction and operation of the reservoirs (pre-1984 for Thomson, pre-1957 for Upper Yarra and around pre-1926 for O'Shannassy and Maroondah) were derived based on flow correlation with the nearby stream gauging records or catchment area adjustment. For Graceburn Creek, the entire recorded monthly flow just upstream of the weir (non-impacted flow) was used in this study, as some of the flow at the weir had been diverted into the Maroondah Reservoir since 1941, depending on operational conditions. The monthly flow record at the Melbourne Water major harvesting reservoir sites represents the main sources of streamflow from Melbourne's water supply catchments which are not impacted by upstream diversions, but may be impacted by changes to the catchment (see further elements in the 'Discussion' section).

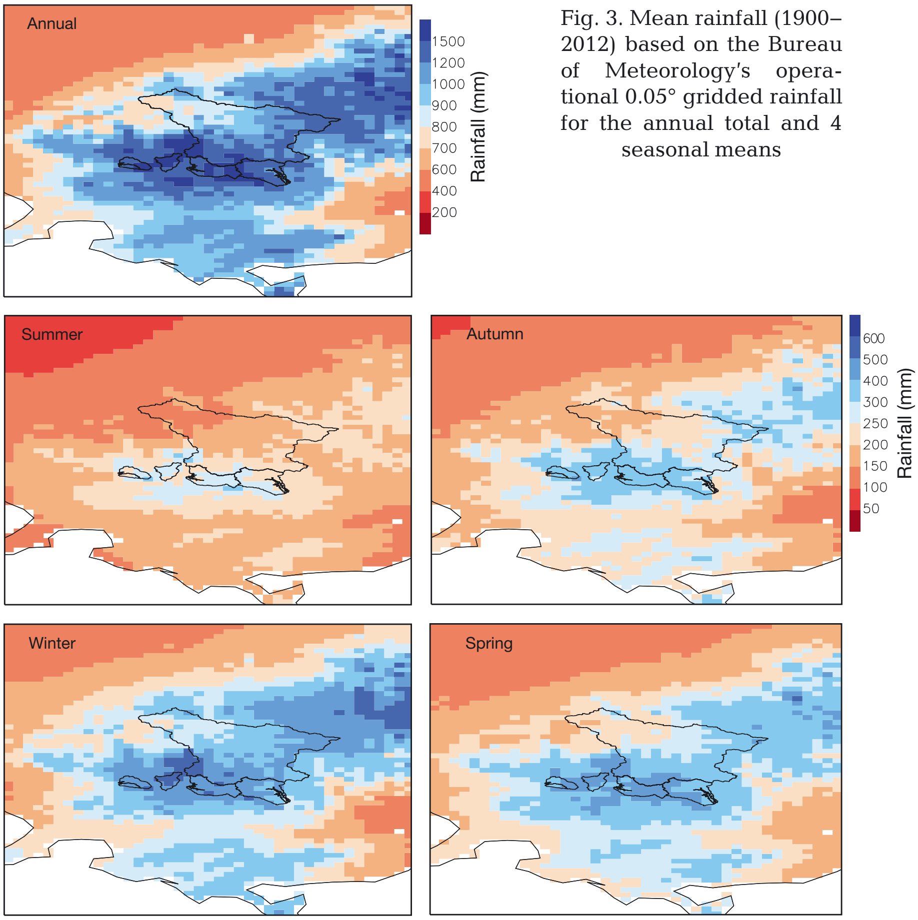

Fig. 3. Mean rainfall (1900–2012) based on the Bureau of Meteorology's operational 0.05° gridded rainfall for the annual total and 4 seasonal means

The long-term annual mean gridded rainfall, as well as the mean for the 4 calendar seasons from 1900 to 2012, is shown in its native grid (approximately 5 km squares) across the area of interest (Fig. 3). As expected, rainfall is higher over the significant topography, and the highest rainfall is observed in winter. This is consistent with the main characteristics of the mid-latitude rainfall systems (frontal and cut-off lows) travelling from west to east across the region. In particular, in winter, the maximum rainfall is on the west-facing slopes at high elevation — O'Shannassy and the southern part of the Eildon catchment area. Spring is wetter than autumn. This picture is very relevant for the Murray part of the MDB, as most of the run-off is generated in these high-elevation areas.

Factors known to influence run-off are rainfall, soil moisture and evaporation. In this study we used the rainfall of the current month as the first predictors of the monthly streamflow data. Additional contributions to the pre-conditioning of the soil come from the rainfall of the month immediately past, as well as the rainfall over the previous 12 mo. In addition, we also considered the role that maximum temperature can play on streamflow via evaporation by using the average maximum temperature over the current month (based on the same operational gridded BoM dataset). While the role of temperature on evaporation is well established by the Penman-Monteith equation, its impact on the complex evapo-transpiration aggregated over a vegetation-covered landscape is debatable (see Smith & Power 2014). Some early studies suggested that warmer temperatures made an important contribution to the anomalously dry conditions experienced in the MDB region of eastern Australia during the prolonged drought of 1996–2010 (Nicholls 2004, Cai et al. 2009). However, this explanation has been disputed by Lockart et al. (2009). There is no evidence that temperature increases can explain this changed relationship. A more likely explanation, as proposed by others, is that it reflects the combined effects of changes in timing of rainfall events throughout the year, the absence of very heavy rainfall events and, most likely, long-term changes in groundwater levels (Larsen & Nicholls 2012). Studies combining all these effects with temperature anomalies suggested a much more reduced contribution from temperature than originally thought (CSIRO 2012 and the references within).

Temperature data are available from 1910 onward, rainfall data from 1900 onward and streamflow data from 1913 onward. A multi-linear regression approach was used based on the observed relationship between the atmospheric variables and streamflow for the full 1913–2012 record. Several attempts have been made to linearly reconstruct the monthly streamflow data using these predictors; 5 are reported here in order to document the importance of several factors as well as the possibility of spurious skill due to over-fitting of the dataset:

(1) R_1 is the most complete reconstruction and combines current monthly rainfall with the rainfall of the previous month, the rainfall of the previous 12 mo (not including the current month), as well as the temperature of the month

(2) R_2 repeats R_1 but using a fully cross-validated approach

(3) R_3 repeats R_1 but with the influence of the temperature of the month removed

(4) R_4 repeats R_3 but with the influence of the rainfall of the previous 12 mo removed

(5) R_5 repeats R_4 but with the influence of the rainfall of the previous month removed

While these are very clear simplifications of complex hydrological processes occurring at small sub-catchment scale, the focus here is to see how much of the catchment-wide streamflow can be captured with this simple approach as an alternative to using the hydrological models of varying complexity (e.g. storage routing) used in many other studies.

3. RESULTS

3.1. Rainfall and streamflow variability in recent decades

In order to characterise the specificities of the MD across the catchments that were considered in this study and to put them into the broader perspective of the SEA and MDB, we compared the MD to the previous driest periods on record for each area. It was found that the earlier driest periods of similar duration on record were centred around 1940 for the MDB and SEA and around 1910 for the Melbourne Water catchments and for Eildon. The rainfall deficit as a percentage of the long-term mean, the magnitude of the wettest years during both dry periods, and the seasonality of the decline were of particular interest (Table 1).

While the choice of 13 yr was arbitrary, Timbal & Fawcett (2013) extensively studied other drought durations (between 3 and 21 yr) and found that the MD was worse than anything observed using an extended instrumental record. In this study, our focus was on smaller catchments, but, as shown in Table 1, the MD was far worse than anything else in the instrumental record. For the Eildon catchment, the largest previous rainfall deficit was 8% (over a 13 yr period: 1902–1914). This is a remarkably small percentage compared with the deficit of 18% observed during the MD. For Melbourne Water catchments, the previous driest 13 yr periods were even less remarkable, never exceeding a 5% deficit. Another clear difference between the MD and previous historical droughts was the absence of very wet years; e.g., in both Eildon and Yarra catchments, there was no single year above the long-term average for the 13 yr of the MD. In comparison, during a previous long-term drought, rainfall years well above average were observed (up to 15% above the long-term average). The seasonality of the rainfall deficit was also markedly different. During the MD, the autumn deficit was the largest in percentage terms, almost 30%, whilst the other seasons had decreases of 7 to 16%. For the 1902–1914 drought, the decline was predominantly in the summer (about 10%), and the

Table 1. Characteristics of the Millennium Drought (MD) (1997–2009) compared to the next most intense lowest 13 yr period (PD) on record not overlapping with the MD across 5 areas of interest: the Murray-Darling Basin (MDB), the Eildon catchment, the Melbourne Water major catchments (Yarra and Thomson) and south-eastern Australia (SEA) as a whole. Data presented as MD/PD. The rainfall deficit and anomalies are given as percentages of the long-term mean. The annual rainfall (mm) of the wettest year embedded within the 13 yr droughts is indicated, as well as the ranking of that year. For both the MD and previous lowest 13 yr on record, seasonal anomalies are also indicated in percentage terms. All statistics are based upon the complete 1900–2012 dataset

	MDB	Eildon	Yarra	Thomson	SEA
Previous dry period	1934–1946	1902–1914	1902–1914	1902–1914	1937–1949
Rainfall deficit	−15/−13	−18/−8	−17/−4	−15/−5	−12/−8
Wettest year					
Total rainfall	577/543	1090/1284	1476/735	1420/1566	611/697
Ranking	15/25	62/23	61/19	49/22	44/13
Summer anomaly	−6/+11	−8/−10	−8/−8	−8/−9	−6/+8
Autumn anomaly	−24/−16	−29/−1	−25/+1	−24/−4	−26/−5
Winter anomaly	−4/−7	−16/+1	−13/2	−12/+1	−9/−11
Spring anomaly	+3/−26	−12/−5	−14/−5	−13/−3	−6/−13

other seasons all had declines of <5%; winter, the key season for streamflow, showed values close (±2%) to the long-term average for Eildon and all Melbourne Water catchment areas.

The annual cycle of rainfall in each of the 4 catchment areas highlighted the differences between the extended MDB, which had a broad summer maximum for rainfall and a smaller early winter peak in June, and the catchments across the GDR, where rainfall was predominantly a cool-season (April–October, peaking in July) phenomenon (Fig. 4). The bi-modal nature of the annual cycle reflected the large latitudinal extent of the MDB (about 38–24° S), with a northern basin dominated by warm-season rainfall and the southerly Murray Basin dominated by cool-season rainfall. During the MD, the dry conditions in the southern catchments were apparent over the whole year, but they were worse for the half of the year when monthly temperatures were below the annual mean (i.e. the cool season). Dry conditions in the MDB were limited to the cool season, with a small increase during the warm season. The consequences of rainfall deficiency during the MD on streamflows in the 3 southerly catchments were considerable. The largest reduction in streamflow in absolute terms was in winter and spring which are the peak seasons for streamflow, while the largest rainfall decline occurred in autumn. In percentage terms, nevertheless, the annual cycle of streamflow reductions matched the rainfall deficiency being greatest in autumn; this illustrates the importance of autumn rainfall in saturating the catchment prior to winter rains.

2010—when the MD ended—together with 2011 were the wettest 2 yr recorded across Australia (Bureau of Meteorology 2012). For the 2 catchment areas north of the GDR—MDB and Eildon—2010 was extremely wet, ranking 1st and 7th, respectively, out of the 110 yr record (Table 2). Further south (Yarra and Thomson), the 2010 rainfall was above the long-term mean but only ranked 29th and 26th, respectively, for the 113 yr record (decile 8), well short of the highest values on record established during the 1950s or 1970s depending on catchments. That north–south difference in ranking was less apparent in 2011, with rainfall ranking between 11 and 36 for all catchments considered. These annual totals hide very contrasting seasonal behaviours. Dividing the rainfall into the warm months of the year (November–March) and the cold months of the year (April–October), the record-breaking rain came during the warm months of the year, whereas the cool-month rainfall was close to or below the long-term average in 2010 and 2011 across the Yarra and Thomson catchments. While in Eildon, the cool-month rainfall was above average in 2010, but below average in 2011, similar to SEA and the entire MDB. The rainfall patterns, on average for 2010 and 2011, when compared to the long-term mean (Fig. 5) underline that, across the catchments of interest, the largest differences occurred in summer and spring, while the winter and autumn maps were similar to the map of the long-term mean. During the 2 yr wet period, total rainfall during the warm season across the area was generally higher than the total rainfall during the cool season; this contrast was significant for the entire MDB and for the Eildon catchment north of the GDR in comparison with the Yarra and Thomson catchments south of the GDR.

The extent of the recovery in comparison with the extent of the MD deficit differed markedly between the entire MDB and the Eildon catchment north of

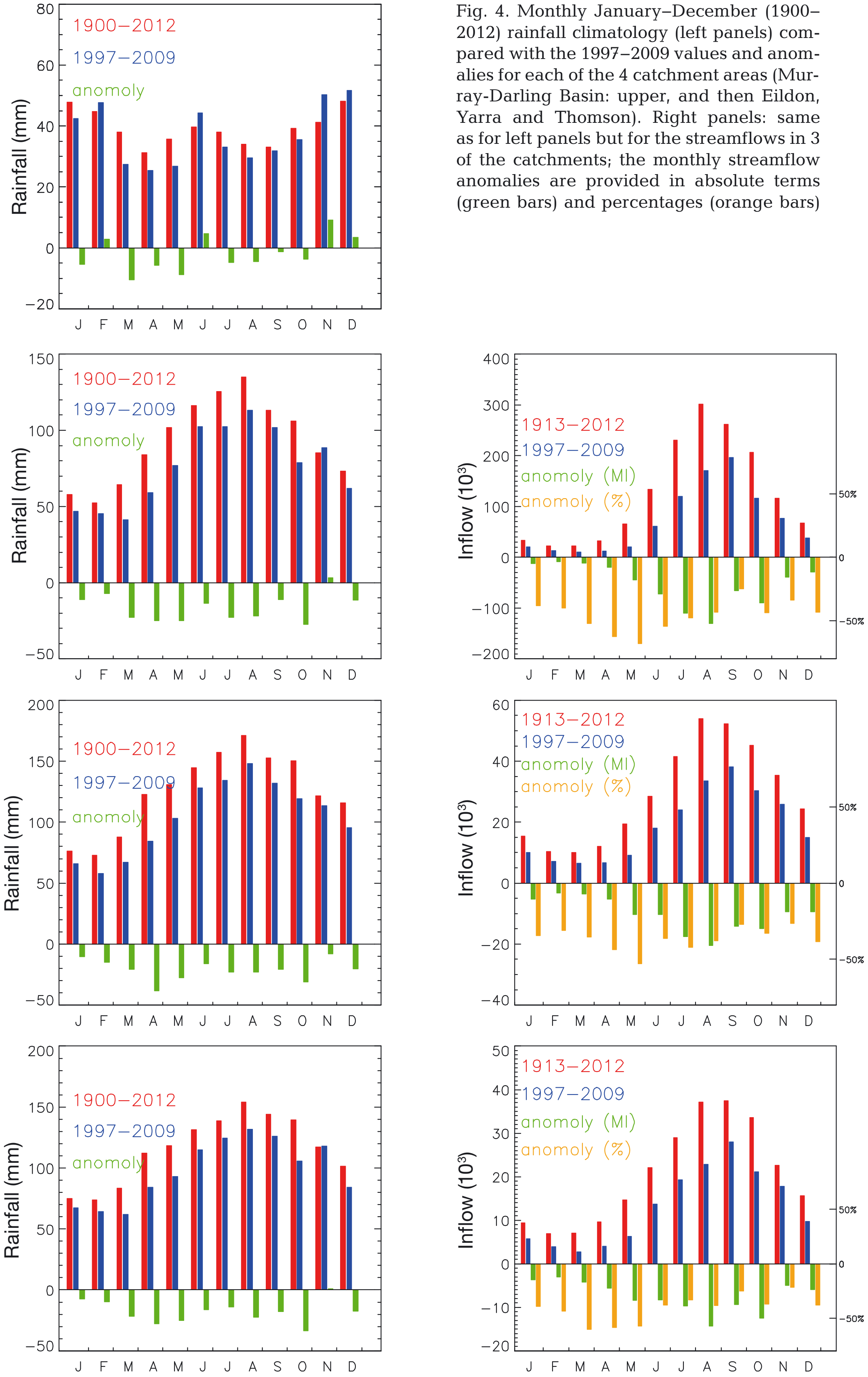

Fig. 4. Monthly January–December (1900–2012) rainfall climatology (left panels) compared with the 1997–2009 values and anomalies for each of the 4 catchment areas (Murray-Darling Basin: upper, and then Eildon, Yarra and Thomson). Right panels: same as for left panels but for the streamflows in 3 of the catchments; the monthly streamflow anomalies are provided in absolute terms (green bars) and percentages (orange bars)

Table 2. Statistics for 2010 and 2011 rainfall and comparisons with the highest rainfall for 1900–2009 (in mm, with the year it happened in parentheses) as a bench mark for the 5 areas of interest described in Table 1. Annual rainfall (mm) and rankings are provided for 2010 and 2012 (rankings are based on the full 1900–2011 dataset) cool months (April–October) and warm months (January–March and November–December). **Bold**: record-breaking statistics. Abbreviations as in Table 1

Catchment	Highest annual rainfall 1900–2009	Annual rainfall (ranking)		Long-term mean		1997–2009		2010		2011	
		2010	2011	2010 Warm	2011 Cool	Warm	Cool	Warm	Cool	Warm	Cool
MDB	784 (1956)	**807 (1)**	600 (13)	259	212	255	191	**538 (1)**	269 (21)	432 (5)	168 (86)
Eildon	1724 (1956)	1516 (7)	1226 (36)	439	676	363	556	**800 (1)**	717 (48)	664 (7)	564 (87)
Yarra	2275 (1952)	1702 (29)	1721 (26)	626	879	520	730	818 (11)	884 (57)	886 (6)	833 (69)
Thomson	2245 (1952)	1557 (26)	1602 (18)	591	799	501	675	781 (11)	773 (65)	816 (6)	785 (60)
SEA	878 (1956)	811 (4)	718 (11)	261	323	236	279	**469 (1)**	342 (42)	450 (3)	267 (84)

the GDR and the Yarra and Thomson catchments south of the GDR. These quantities were expected to oscillate around zero, but, for the 16 yr (192 mo) shown (Fig. 6), sizeable deficits were obvious. Across the southerly catchments, the deficit for the MD (1997–2009) was only partially offset by the subsequent recovery in 2010–2011 at the very end of the 16 yr period; the accumulated deficit was still larger than at any time in the past instrumental record prior to the onset of the MD in 1997 (the previous 16 yr period of lowest rainfall drawn from the 1900–1996 record is considered in Fig. 6 to provide that historical benchmark). The magnitude of the record-breaking nature of the MD for the 3 southern catchments was clearly shown. In contrast, the recovery from the long-term perspective was relatively modest in all 3 catchments, except in the Eildon catchment north of the divide, where the recovery was sizeable.

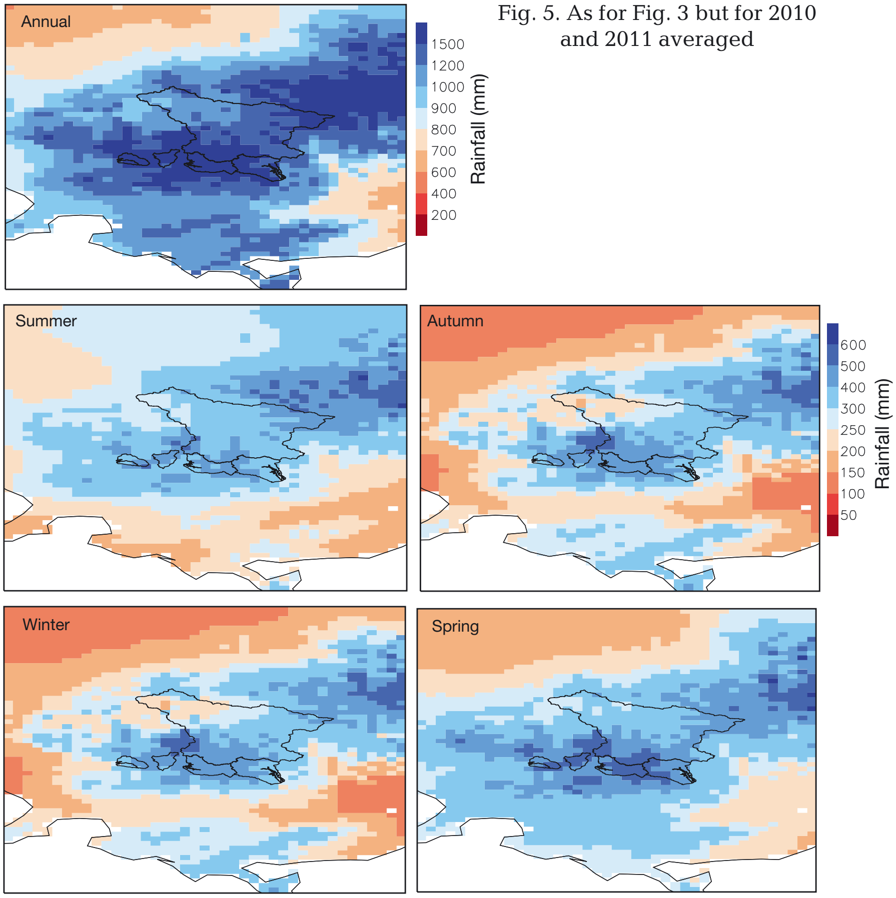

Fig. 5. As for Fig. 3 but for 2010 and 2011 averaged

3.2. Large-scale modes of natural variability on rainfall and reservoir streamflows

Australia is affected by many types of weather system; the frequency and magnitude of these are often influenced by several large-scale features of atmospheric circulation (Risbey et al. 2009). The most well-known and best-documented natural large-scale modes emanate from tropical oceans, primarily in the Pacific, e.g. ENSO and its response in the Indian Ocean, as measured by the IOD index proposed by Saji et al. (1999). To investigate these large-scale influences on high-elevation catchments we used 2 indices based on tropical SSTs. Niño4 (N4) is the classic index of ENSO variability based on central Pacific SST anomalies and the tripole is an index developed by Timbal & Hendon (2011) encompassing the anomalies of all tropical SSTs strongly related to

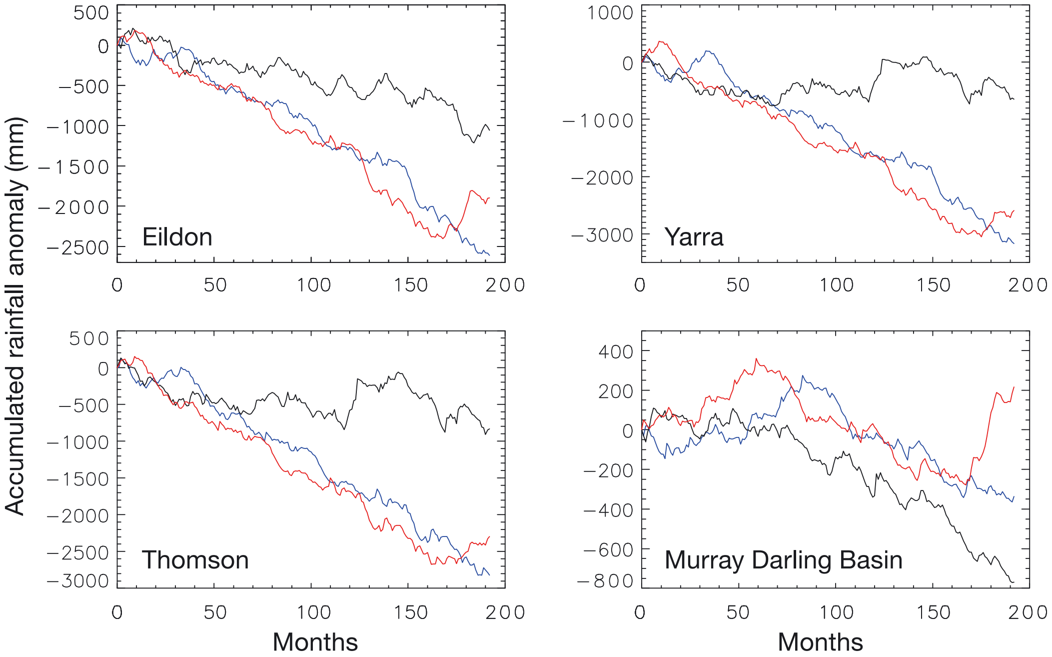

Fig. 6. Accumulated rainfall anomalies for each of the catchment areas for 3 different time periods. Red: deficit for 1997–2012; blue: deficit for 1994–2009 period, encompassing the Millennium Drought which in all cases was the 16 yr period of lowest rainfall on record; black: 16 yr period with the lowest accumulated deficit prior to 1994

SEA rainfall, and hence capturing the additional effect of the IOD on Australian rainfall.

In addition, regional indicators are used which, on the one hand, respond to remote modes of variability and, on the other hand, respond to broad-scale changes in mean meridional circulation which influence the climate of SEA via the mean sea level pressure (MSLP) controlling local rainfall and streamflow (CSIRO 2012). The sub-tropical ridge (STR) intensity and position computed by Drosdowsky (2005) have been shown to tightly control SEA rainfall during the cool season (Timbal & Drosdowsky 2013), and are used in this study. The geographical locations of these indices are summarised in Fig. 7.

Monthly correlation coefficients between both rainfall and streamflow (not shown) and the 4 climate indices for each of the 4 catchments were very weak and not significant from November to March, but were statistically significant from April to October in most instances. This was explored further for the key seasons of winter and spring (Fig. 8), when the relationships were usually stronger and statistically significant and when the bulk of the streamflow was generated. Higher correlation coefficients with the tripole than with the N4 index were noted everywhere and were consistent with the fact that the tripole was constructed to maximise these correlations across SEA. The added value of the tripole versus the classic N4 was obvious in winter, where correlation coefficients for N4 failed to reach the 99% significance level across the entire region.

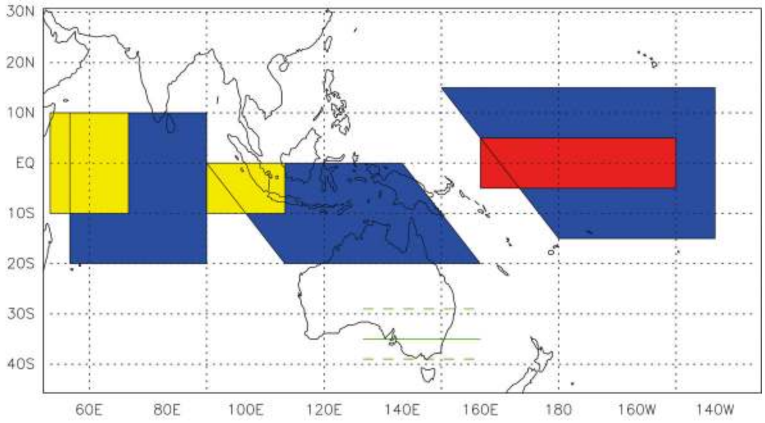

Fig. 7. Location of indices of large-scale modes of variability used in this study: Niño4 sea-surface temperature region (red rectangle), Saji et al. (1999) Indian Ocean Dipole (IOD, yellow boxes), Timbal & Hendon (2011) tropical tripole (blue polygons), Drosdowsky (2005) subtropical ridge position (green lines—solid line: mean annual position; dashed lines: northern [winter] and southern [summer] extents)

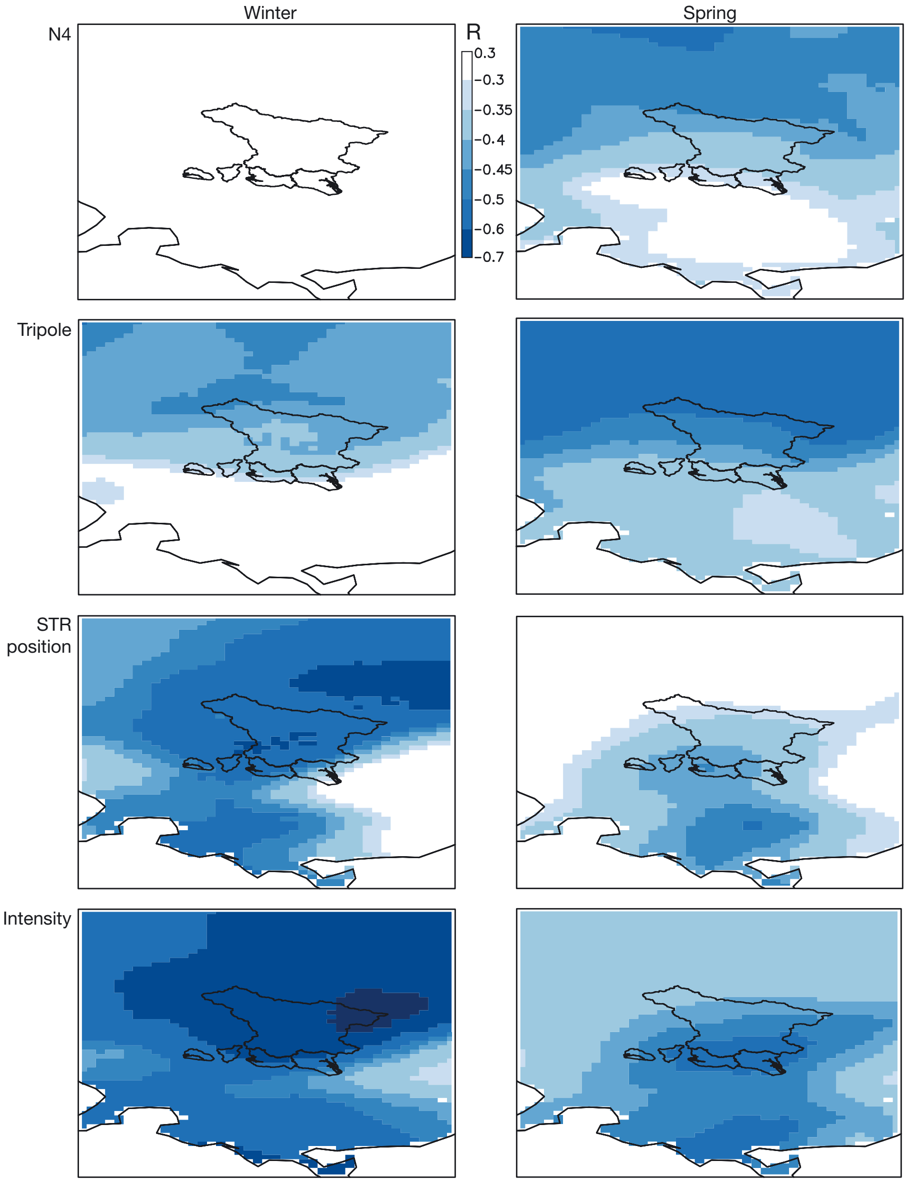

Fig. 8. Correlation coefficients in winter (left panels) and spring (right panels) between rainfall and climate indices (Niño4, top row; the tripole, second row; sub-tropical ridge position, third row; intensity, fourth row)—see Section 3.2 for more details. Correlations coefficients >±0.25 are significant at the 99% level. Correlation coefficients were computed on time-series from 1913 to 2012

However, by and large, both the STR position and intensity were more important in controlling year-to-year variability across the Victorian catchments than were tropical modes. Contrary to tropical influences, the STR had a stronger relationship across the entire region in winter than in spring. South of the GDR, the reduction from winter to spring was marginal; hence, by spring the area with the strongest control on rainfall from the STR shifted from being north of the GDR to being south of it. Spatial features were very similar for STR intensity and position; the stronger relationship was always intensity over position, consistent with previous studies (Timbal & Drosdowsky 2013, Whan et al. 2013).

The relationship between streamflow and the state of tropical oceans was investigated by building composites from both the long-term historical period and during the more recent MD and subsequent recovery in 2010 and 2011. We computed composites based on tripole annual values which, by and large, were consistent with known values for ENSO and IOD years (Fig. 9). A few exceptions were noted in 1928 and 1929, when a negative tripole was associated with El Niño years; in 1933, when a positive tripole was associated with La Niña years; in 1999, when a high positive tripole year was not associated with either La Niña or IOD years; and 1918, 1930, 1960 and 1961, when negative tripole years were not linked with ENSO or IOD variability. Composites were computed based on positive or negative tripole years and compared with averages; the data were split into 2 periods: 1910–1996 and 1997–2012 (Fig. 10). This compositing demonstrated that tropical modes of variability continued to have the same effect on a year-to-year basis, i.e. positive tripole years were wetter than average and negative tripole years were drier than average. This finding, while lacking statistical robustness due to the short sampling (only 4 positive and negative tripole years since 1996 were included in the composites), was consistent with a large body of evidence indicating neither observed change in the teleconnections between tropical modes of variability and the Australian climate nor an expected alteration in this relationship due to future climate change (CSIRO and Bureau of Meteorology 2015). Since 1996, tropical modes of variability have continued to influence streamflow but from a reduced mean. This has been related across the entire SEA to a strengthening of the sub-tropical ridge (Timbal &

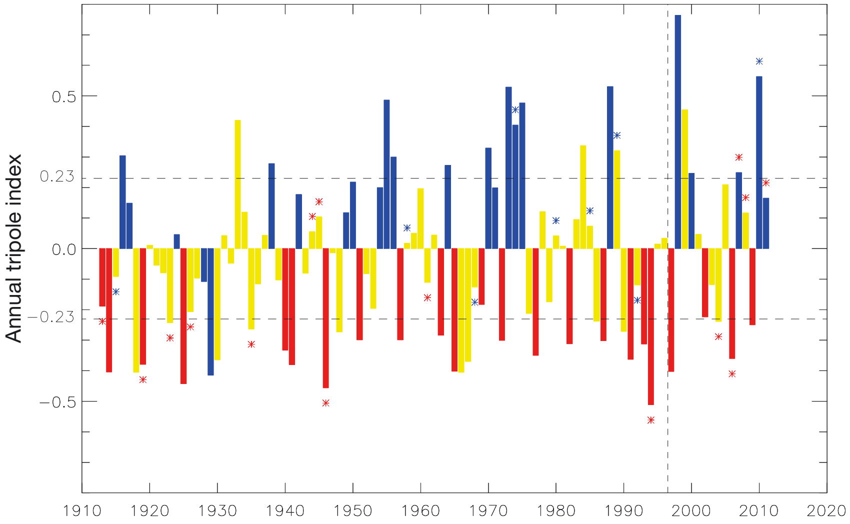

Fig. 9. Time-series (coloured bars) of the annual tripole index. The colours of the bars show significant El Niño (red) and La Niña (blue) years, with yellow being neutral; coloured stars show significant positive (red) and negative (blue) Indian Ocean Dipole years. Horizontal dashed lines: ±0.8 standard deviation of the tripole index separating either positive or negative tripole years from neutral years; vertical dashed line: start of 1997

Drosdowsky 2013). The shift was particularly marked for Melbourne Water catchments, with almost no overlaps between the 2 envelopes. This clearly indicates that the GDR played a role in limiting the tropical influence across Melbourne catchment and in enhancing the long-term drying trend since 1996. Beside the overall reduction, it has also been noted that the peak streamflow month has now been delayed from August (for the pre-1997 period) to September (in the post-1996 period). This could possibly be the effect of drier autumn conditions, with lower antecedent catchment conditions at the start of winter months, coupled with reduced rainfall, leading to reduced runoff generation efficiency and a delay in peak monthly streamflow.

3.3. Using catchment rainfall to estimate reservoir streamflow

Using simple linear models described in an earlier section we attempted to reconstruct streamflow using high-resolution gridded rainfall and temperature data. Key statistics for reconstructed streamflows are presented and compared to observed rainfall and streamflow (Tables 3 & 4). The ability to reproduce the observed streamflow decreased when the number of explanatory hydro-climate variables was reduced. For all statistics, rainfall at lag was an important parameter, either from the previous month (R_4 versus R_5) or from the previous 12 mo (R_3 versus R_4); the impact of temperature was very marginal (R_1 versus R_3).

Explained variances (i.e. squared correlation coefficients) were high and significant (Table 3) even for the simplest approach, but they grew to exceed 0.9 when multiple explanatory variables were used. This was not reduced by the full cross-validation done for the most complete reconstruction (R_2 versus R_1). The improvement in the amount of variance reconstructed was noteworthy, rising to close to 80% for the multiple variable reconstructions; however, it is worth noting that full cross-validation revealed that part of the gain may be spurious (compare R_2 and R_1 amounts of observed variance reproduced in Table 3). In addition to the year-to-year variability, these reconstructions captured trends well (both long and short term). We chose to look at 3 different time periods: the Millennium Drought (1997–2009), the recent period (1980–2012) and the entire period for which we have data (1913–2012). Results from the fully cross-validated approach (R_2) were not meaningful for the full historical period and, therefore, are not reported.

There was a net decrease in streamflow for each time period and for each catchment (Table 4). Over the last 30 yr the most complicated reconstruction captured the trend well (R_1). Similarly, the magnitude of the decline in streamflow during the MD, which has been reported to be larger than expected according to the well-established rainfall–runoff elasticity relationship (Potter et al. 2010, CSIRO 2012 and references within), was well captured (in particular for Eildon and Yarra, less so for the Thomson catchment). Furthermore, cross-validation using data from the last 30 yr (R_2) ensured that these results were not spurious.

Contrary to the recent trend and intensity of the MD, only half the secular trend, at best, was captured by the more comprehensive model. In light of the model's ability to reproduce the more pronounced

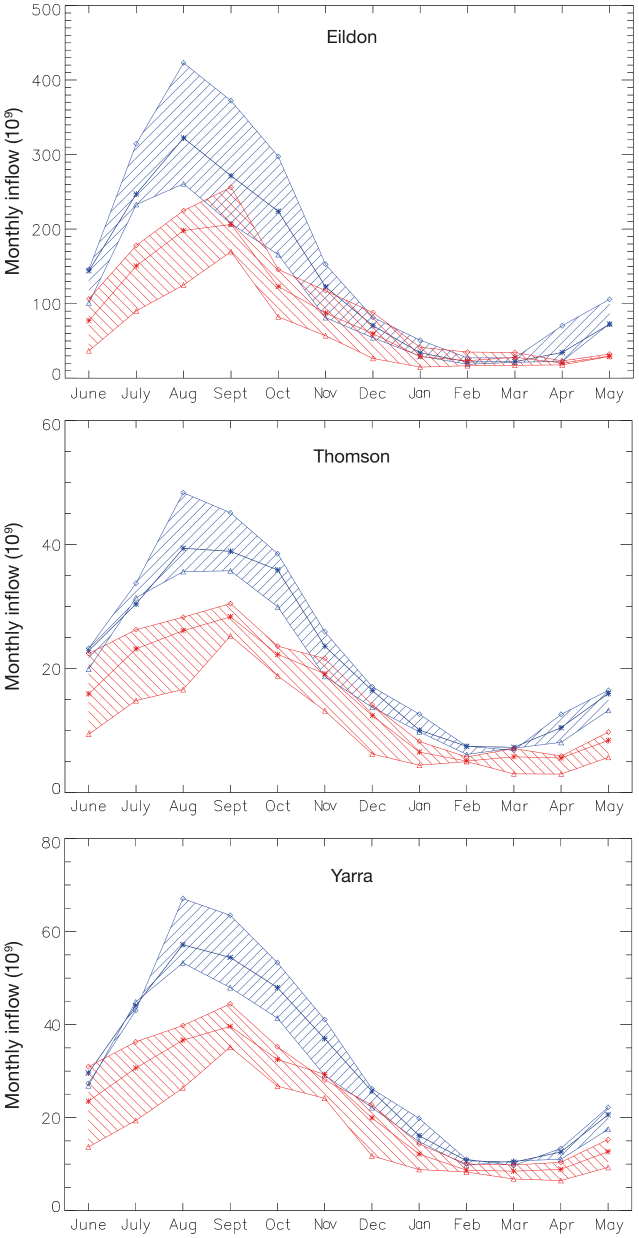

Fig. 10. Eildon (upper panel), Thomson (middle panel) and Yarra (lower panel) composite streamflows based on tripole index values. Blue lines: computed using years prior to and including 1996; red lines: composites computed since and including 1997; lines with stars: means over the period; lines with diamonds: years with a positive tripole; lines with triangles: years with a negative tripole

trends observed since 1980, this highlights the issue that long-term trends were partly affected by non-stationarity in the number of actual observations used in the rainfall grid (see Section 2 and Fig. 2 for details), thus preventing the model from matching the trend in the longer term streamflow record.

Table 3. Inter-annual variance explained (squared correlation coefficients or percentage of the variability captured by the reconstruction) and percentage of the observed variance ranges (given as percentage of variance) reproduced by the reconstructions. All statistics were computed using the entire series from 1913 to 2012 and for the 5 linear reconstructions (see Sections 2 and 3.3 for details): predictors were rainfall for the month (R), rainfall from the previous month (R_{-1}), rainfall from the previous 12 mo (R_{-12}) and temperature for the month (T)

Reconstruction	Predictors	Eildon	Yarra	Thomson
R_1	R, R_{-1}, R_{-12}, T	0.90 / 84	0.85 / 78	0.77 / 74
R_2	R, R_{-1}, R_{-12}, T	0.90 / 80	0.85 / 72	0.81 / 51
R_3	R, R_{-1}, R_{-12}	0.90 / 84	0.85 / 78	0.77 / 74
R_4	R, R_{-1}	0.85 / 64	0.74 / 45	0.74 / 53
R_5	R	0.79 / 34	0.69 / 18	0.69 / 27

Table 4. Statistics for observed rainfall and streamflow, as well as for the 5 linear streamflow reconstructions (see Sections 2 and 3.3 for details) for the 3 catchment areas according to the magnitude of the deficit during the Millennium Drought (1997–2009), the 1980–2012 linear trend and the 1913–2012 linear trend. na: not applicable

	Rainfall	Streamflow	R_1	R_2	R_3	R_4	R_5
1997–2009 anomaly (percentage of long-term mean)							
Eildon	−18	−42	−40	−41	−40	−30	−20
Yarra	−17	−36	−35	−34	−34	−21	−13
Thomson	−16	−37	−30	−28	−30	−22	−15
1980–2012 linear trend (percentage of 1980–2012 mean)							
Eildon	−13	−38	−50	−49	−49	−42	−29
Yarra	−11	−23	−29	−29	−29	−21	−12
Thomson	−7	−18	−19	−15	−17	−14	−10
1913–2012 linear trend (percentage of 1913–2012 mean)							
Eildon	−6	−34	−17	na	−17	−14	−9
Yarra	−8	−34	−16	na	−16	−10	−6
Thomson	−8	−36	−15	na	−15	−11	−8

4. DISCUSSION

4.1. Severity of the MD

From January 1997 to December 2009 SEA experienced its worst long-term drought on record—the MD, the driest 13 yr period since reliable climate records from the mid-18th century. It was different from previous droughts in several ways including lower year to year variability and the seasonality of the rainfall decline. The MD was more severe by a sizeable factor of 3- to 4-fold than previous historical droughts across the entire SEA, but more remarkably so for the catchments dotted across the GDR, in the

State of Victoria, east of Melbourne. The GDR acts as a physical barrier in terms of natural variability, and is the source of high run-off and streamflows into large dams which have been constructed to provide a surface water supply to Melbourne (Yarra and Thomson catchments) and the rest of Victoria north of the GDR (Eildon catchment). The long-term rainfall deficiencies (and streamflow reductions) have led to challenges in water management in Melbourne and across SEA (Post et al. 2014). The previous driest period on record was only a third (Thomson catchment) to less than a quarter (Yarra catchments) of the severity of the rainfall deficit during the MD, which indicates the extreme severity of the MD for these high-elevation, high-yield catchments. This finding confirms an earlier study of the very unusual nature of the MD (Timbal & Fawcett 2013).

The question concerning the stationarity of the rainfall record in recent decades compared to the full historical record was raised by Timbal & Fawcett (2013), who demonstrated — using a longer historical perspective (from 1865 to 2012) — that this was very unlikely across the broader area of southeast Australia. Furthermore, using paleoclimate proxy records from the Australasian region, Gallant & Gergis (2011) developed a reconstruction of streamflow for the Murray River from 1783 to 1988, and estimated that the 1998–2008 streamflow deficit had an approximate 1 in 1500 yr return period. For Melbourne's major water supply catchments, Tan & Rhodes (2013) highlighted that the 10 yr (1997–2006) drought streamflow was estimated to have a <0.2% probability of occurrence (worse than 1 in 500 yr) based on historical streamflow records since 1913, but could become a commonly occurring event in a changing and variable climate, assuming a 'return to dry scenario' similar to that experienced during the recent MD.

4.2. Recovery following the MD

The MD concluded in early 2010. In 2010 and 2011, very high rainfall across the entire Australian continent (highest 2 yr rainfall total across the continent) brought relief to SEA, and most of the reservoirs located in the catchments considered in this study recovered. In 2012, at the end of the refilling season (November), the MDB authority reported its storage capacity to be 100%; Lake Eildon also reached full capacity, while Melbourne Water storage exceeded 80%. These are clear indications that, from a water management perspective, the abundant rainfall in 2010 and 2011 provided the required relief from the MD and helped complete recovery.

However, from a purely climatic perspective, cumulative monthly rainfall anomalies tell a different story regarding the magnitude of the recovery in comparison with the severity of the MD rainfall deficiency; the accumulated rainfall deficit has not recovered in any way similar to historical accumulated deficits. It is worth noting that it is not evident from this analysis whether this matters for the catchments considered; it may have a legacy in terms of ground water recharge, but this was not investigated in our study. For all high-elevation catchments on both sides of the GDR, the recovery of reservoir levels hides some important facts. Despite the 2010–2011 recovery, across the Eildon, Yarra and Thomson catchments, accumulated rainfall deficiencies are still the largest within the historical record prior to the onset of the MD. The rainfall during the recovery was predominantly a warm-season phenomenon, while the long-term deficit was primarily a cool-season phenomenon. Finally, the recovery was spatially uneven, with the largest recovery observed north of the GDR and less so south of the GDR, in Melbourne's water supply catchment areas.

4.3. Role of large-scale drivers

It is well established that rainfall in SEA decreases during El Niño years and during years with positive IOD, and it has been suggested that the MD was due to an extreme number of these years (Ummenhofer et al. 2009), although that idea has since been refuted by several studies (Nicholls 2010, Timbal & Hendon 2011, Smith & Timbal 2012). The analysis of inter-annual variability of rainfall and streamflow across these catchments highlights the importance of the GDR. Large-scale modes of natural variability emanating from tropical Pacific and Indian Oceans are an important source of the observed interannual variability in rainfall and streamflow, but the importance of this is reduced south of the GDR. Tropical modes show a significant north–south gradient of influence, with stronger correlations to the north. Using a tripole index (Timbal & Hendon 2011), it was shown that the SST to the north of Australia and the Indian Ocean response to ENSO play key roles at the onset of the winter–spring period; by spring, the relationships with the tropical indices are stronger throughout the region than they are in winter, but the strong influence of the GDR in limiting the relationship with tropical influences further south across Victoria remains obvious. There is a similar effect further north along the GDR between coastal and inland SEA, which has been explained in terms of moisture flux anomalies and opposing influences between the direct influence of the tropical Pacific Ocean and the remote influence of the Indian Ocean (Pepler et al. 2014).

Contrary to teleconnections with tropical oceans, local control of the rainfall due to the belt of high-pressure systems hovering across SEA (the sub-tropical ridge) is particularly strong for the entire winter–spring period in these high-elevation catchments. Rainfall is primarily generated during the cool time of the year by rain-bearing systems travelling from west to east, and their ability to penetrate inland and deliver rainfall is reduced if the STR strengthens or shifts poleward. From a seasonal prediction perspective, the correlations with rainfall are consistently stronger than those with streamflow, in particular with STR indices, and are consistent with the lack of predictability, and hence persistence from month to month, with regards to STR behaviour. The difference is not as pronounced for tropical indices, where correlations are very similar for rainfall and streamflows in spring, thus confirming that, because of their predictable and persistent nature, tropical modes of variability can be used to predict streamflows and complement the persistence from month to month which exist in streamflow (Robertson & Wang 2012).

For the catchments east of Melbourne, since 1997, there has been a definite shift to lower streamflow during the June–November dam-filling season. This is the period of greatest rainfall and is therefore critical to water management. Since 1997, high streamflow years due to a positive influence from the tropics (i.e. positive tripole) have provided similar streamflow to low-streamflow years due to a negative tropical influence (i.e. negative tripole) prior to 1996. It is clear from that analysis that, while tropical modes of variability remain important to discriminate between high-streamflow and low-streamflow years, the marked reduction of streamflow during the MD and recovery period in 2010–2012 is not explained by these modes. Instead, we continued to observe year-to-year variability driven by these modes (as was the case during the wet 2010 and 2011 La Niña episodes or during the very dry 2006–2009 repeated positive IOD episodes), but applied to a different and lower baseline for mean streamflow. In the meantime, other studies have reported that the reduction in rainfall across SEA, which is driving the streamflow reduction in these southerly catchments, is primarily due to a strengthening of the STR, potentially associated with global warming (Timbal & Drosdowsky 2013).

4.4. Relationships between rainfall, temperature and streamflow

The ability to reproduce monthly streamflow variability using solely the rainfall observed across the catchments over different time scales and combined with temperature was investigated. For this part of the study, the focus was on Eildon, Thomson and Yarra catchments. These southern catchments are smaller in scale and have higher rainfall than the MDB; thus, it is more likely that the streamflow can be successfully captured by using catchment-wide rainfall averages. In addition, because of the complex anthropogenic influence across the MDB, it is unlikely that a simple relationship can be found between rainfall, temperature and streamflow. It was found that when current rainfall, rainfall from the previous month and rainfall from the previous 12 mo are used as explanatory variables in the multiple linear regression models, most of the annual streamflow variability can be reasonably reproduced, including the decline in the last 30 yr and the severity of the streamflow decline during the MD. In contrast to rainfall, temperature does not appear to play a significant role, as discussed previously by Potter et al. (2010) and Smith & Power (2014) and the references in the latter. This was tested several times using various combinations with and without temperature (not all results are shown here for the sake of brevity). However, it is fair to say that in all attempts rainfall of the month was always used; hence, it is possible that, due to the dependence between rainfall and temperature (i.e. wet days are cold days), once rainfall is used, the effect of temperature on streamflow is already captured. Overall, for future use of this simple approach, testing both the optimal combination (with temperature) and a reduced combination (without temperature) would be worthwhile. Furthermore, we confirmed, using a fully cross-validated approach, that the ability of the most complete linear combination to reproduce streamflow characteristics during the last 30 yr was not a statistical artefact.

The long-term persistence for rainfall (previous 12 mo), which represents groundwater or deeper antecedent soil moisture conditions, is important, while short-term and current rainfall conditions are not sufficient. Simulation of the long-term persistence in streamflow decline observed during the MD was found to be a useful variable, and supplements the long-term rainfall-runoff elasticity observed in the past. This idea could be pushed further (i.e. using the prior 10 yr rainfall mean) to capture decadal shifts linked to the Inter-decadal Pacific Oscillation (IPO) which has a signature of SEA streamflow (Pui et al.

2011). The fact that antecedent catchment conditions ranging from a few months to a year can have large impacts on streamflow is well known and has been shown previously for Melbourne Water catchments. Tan et al. (2012) investigated the runoff responses for Melbourne's major water supply catchments under 2 vastly different climate scenarios. The results indicated that, given the moderately wet antecedent catchment conditions at the start of 2012, the simulated runoff (assuming a repeat of the 2006 observed daily rainfall sequences — a very low rainfall year) would remain higher for 3–4 mo before returning to the very low runoff conditions similar to a dry year like 2006. In comparison, the simulated runoff (assuming a repeat of the 2011 observed daily rainfall sequences — a relatively high rainfall year) would remain lower for a longer period of about 6–8 mo before returning to the higher runoff conditions similar to a wet year like 2011.

It was also noted that an observed secular decline in streamflows was not well captured by these reconstructions, but credible evidence exists that this is likely due to a data issue. In the data section, it was noted that, for rainfall, the coverage was sparse in the earlier part of the record, with an absence of high-elevation stations. This likely leads to a spurious positive trend; hence, it is possible that the actual long-term declining trends of rainfall are more pronounced than that deduced from the gridded observed rainfall and used in the reconstruction, leading to an underestimation in streamflow reduction trends. However, other possibilities are worth mentioning. For example, changes in the accuracy of the streamflow data over time cannot be ruled out (given the flow data prior to dam construction in the Thomson and Yarra catchments were mostly derived based on flow correlation with nearby stream gauging records or catchment area adjustment). It is also possible that differences in catchment soil depth, non-linear hydrologic processes and threshold effects — as well as external changes such as changes in land use or vegetation cover due to bushfire impacts, which cannot be captured by a simple multiple linear regression model — have played a role in recent history. This may be part of the explanation for the fact that, while the streamflow reduction during the MD is fully captured for the Yarra catchments (−35 % reconstructed for −36 % observed), it is captured less effectively for the Thomson catchment (−30 % reconstructed for −37 % observed).

Overall, for these high-yield rainfall catchments, simple linear combinations of observed rainfall across the catchment can reproduce streamflow at a monthly time-scale. This simple analysis opens up the possibility of providing a straightforward estimate of the impact of climate change on these catchments using downscaled climate-change projections on similar grid. This can be done using currently available statistical downscaling techniques (Timbal et al. 2009) that provide projections of future changes in rainfall on a high-resolution grid (Timbal et al. 2011). Such work is underway and will provide a benchmark against which to evaluate more complex approaches relying on several hydrological models of various complexities fed with these downscaled rainfall data (Teng et al. 2012).

5. CONCLUSIONS

The additional knowledge gained in this study on the magnitude of the MD, the size of the 2010–2012 recovery and how these phenomena diverge on different sides of the GDR is very valuable; although only minor differences were found south of the GDR, between the Yarra and Thomson catchments on either side of the north–south ridge. The significant contrast in rainfall patterns during the 2010–2011 recovery between the entire MDB and the Eildon catchment north of the GDR, in comparison with the Yarra and Thomson catchments south of the GDR presents water management opportunities, as all these catchments are inter-connected by the water supply system (e.g. north–south connection). Advancing our understanding of how rainfall varies on inter-annual to longer time scales can help better inform the management of these systems, and potentially enhance water security, for example through inter-basin transfer strategies during times of droughts and floods, and in responses to climate change.

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LITERATURE CITED

Bureau of Meteorology (2012) Australia's wettest two-year period on record; 2010–11. Special Climate Statement No. 38, National Climate Centre, Bureau of Meteorology, Melbourne. Available at: www.bom.gov.au/climate/current/statements/scs38.pdf.

Cai W, Cowan T, Briggs P, Raupach M (2009) Rising temperature depletes soil moisture and exacerbates severe drought conditions across southeast Australia. Geophys Res Lett 36:L21709, doi:10.1029/2009GL040334

Chiew FHS (2006) Estimation of rainfall elasticity of streamflow in Australia. Hydrol Sci J 51:613–625

CSIRO (Commonwealth Scientific and Industrial Research Organisation) (2010) Climate variability and change in south eastern Australia: a synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI). Available at: www.seaci.org/publications/synthesis.html

CSIRO (2012) Climate and water availability in south-eastern Australia: a synthesis of findings from Phase 2 of the South Eastern Australian Climate Initiative (SEACI), SEACI synthesis report. Available at: www.seaci.org/publications/synthesis.html

CSIRO and Bureau of Meteorology (2015) Climate change in Australia: information for Australia's natural resource management regions. Technical Report, CSIRO and Bureau of Meteorology, Melbourne

Drosdowsky W (2005) The latitude of the subtropical ridge over eastern Australia: the L index revisited. Int J Climatol 25:1291–1299

Evans JP, Boyer-Souchet I (2012) Local sea surface temperatures add to extreme precipitation in northeast Australia during La Niña. Geophys Res Lett 39, doi:10.1029/2012GL052014

Gallant AJE, Gergis J (2011) An experimental streamflow reconstruction for the River Murray, Australia, 1783–1988. Water Resour Res 47, doi:10.1029/2010WR009832

Howe C, Jones RN, Maheepala S, Rhodes B (2005) Implications of potential climate change for Melbourne's water resources. A collaborative project between Melbourne water and CSIRO urban water and climate impact groups, Melbourne

Hutchinson MF (1995) Interpolating mean rainfall using thin plate smoothing splines. Int J Geog Inf Sys 9:385–403

Jones DA, Weymouth G (1997) An Australian monthly rainfall dataset. Technical Report 70, Bureau of Meteorology, Melbourne

Jones DA, Wang W, Fawcett R (2009) High quality spatial climate data sets for Australia. Aust Meteorol Oceanogr J 58:233–248

Kiem AS, Verdon-Kidd DC (2009) Climate drivers of Victorian streamflow: Is ENSO the dominant influence? Aust J Wat Resour 13:17–29

Kiem AS, Verdon-Kidd DC (2010) Towards understanding hydroclimatic change in Victoria, Australia — preliminary insight into the 'Big Dry'. Hydrol Earth Syst Sci 14:433–445

Larsen SH, Nicholls N (2012) The nature of the recent rainfall decrease in the vicinity of Melbourne, southeastern Australia, and its impact on soil water balance and groundwater recharge. Aust Meteorol Oceanogr J 62:11–18

Leblanc M, Tweed S, Van Dijk A, Timbal B (2011) A review of historic and future hydrological changes in the Murray-Darling Basin. Global Planet Change 80-81:226–246

Lockart N, Kavetski D, Franks SW (2009) On the recent warming in the Murray-Darling Basin: land surface interactions misunderstood. Geophys Res Lett 36:L24405, doi:10.1029/2009GL040598

Nguyen H, Timbal B, Smith I, Lucas C (2013) The Hadley Circulation in reanalyses: climatology, variability and expansion. J Clim 26:3357–3376

Nicholls N (2004) The changing nature of Australian droughts. Clim Change 63:323–336

Nicholls N (2010) Local and remote causes of the southern Australian autumn–winter rainfall decline, 1958–2007. Clim Dyn 34:835–845

Pepler A, Timbal B, Rakich C, Coutts-Smith A (2014) Indian Ocean Dipole overrides ENSO's influence on cool season rainfall across the Eastern Seaboard of Australia. J Clim 7:3816–3826

Post DA, Moran RJ (2013) Provision of usable projections of future water availability for south-eastern Australia: the south eastern Australian climate initiative. Aust J Wat Resour 17:135–142

Post D, Timbal B, Chew F, Hendon H, Nguyen H, Moran R (2014) Decrease in south-eastern Australia water availability linked to ongoing Hadley cell expansion. Earth Future 2:231–238

Potter NJ, Chiew FHS, Frost AJ (2010) An assessment of the severity of recent reductions in rainfall and runoff in the Murray-Darling Basin. J Hydrol 381:52–64

Preston B, Jones R (2008) Evaluating sources of uncertainty in Australian runoff projections. Adv Water Resour 31:758–775

Pui A, Lal A, Sharma A (2011) How does the Interdecadal Pacific Oscillation affect design floods in Australia? Water Resour Res 47, doi:10.1029/2010WR009420

Risbey JS, Pook MJ, McIntosh PC, Wheeler MC, Hendon HH (2009) On the remote drivers of rainfall variability in Australia. Mon Weather Rev 137:3233–3253

Robertson DE, Wang QJ (2012) A Bayesian approach to predictor selection for seasonal streamflow forecasting. J Hydrometeorol 13:155–171

Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363

Smith I, Power S (2014) Past and future declines in rainfall and inflow into Perth (Western Australia) dams. J Hydrol Reg Stud 2:84–96

Smith I, Timbal B (2012) Links between tropical indices and southern Australia rainfall. Int J Climol 32:33–40

Tan KS, Rhodes BG (2013) Drought severity estimation under a changing climate. Aust J Wat Resour 17:143–151

Tan KS, Crawford-Wilson P, Rhodes B (2012) Assessing catchment runoff responses under dry and wet year scenarios — a case study. In: Proc 34th Hydrology and Water Resources Symp. Engineers Australia, Sydney, p 1157–1164

Teng J, Chiew FHS, Timbal B, Wang Y, Vaze J, Wang B (2012) Assessment of an analogue downscaling method for modelling climate change impact on runoff. J Hydrol (Amst) 472/473:111–125

Timbal B (2009) The continuing decline in south-east Australian rainfall — update to May 2009. CAWCR Res Let 2:4–11

Timbal B, Drosdowsky W (2013) The relationship between the decline of south eastern Australia rainfall and the strengthening of the sub-tropical ridge. Int J Climatol 33:1021–1034

Timbal B, Fawcett R (2013) An historical perspective on south eastern Australia rainfall since 1865. J Clim 26:1112–1129

Timbal B, Hendon H (2011) The role of tropical modes of variability in the current rainfall deficit across the Murray-Darling basin. Water Resour Res 47:W00G09, doi:10.1029/2010WR009834

Timbal B, Murphy B (2007) Observed climate change in south-east of Australia and its relation to large-scale modes of variability. BMRC Res Lett 6:6–11

Timbal B, Fernandez E, Li Z (2009) Generalization of a statistical downscaling model to provide local climate change projections for Australia. Environ Model Softw 24:341–358

Timbal B, Arblaster J, Braganza K, Fernandez E and others (2010) Understanding the anthropogenic nature of the observed rainfall decline across south-eastern Australia. CAWCR Technical Report 26, Australian Bureau of Meteorology, Melbourne

Timbal B, Wang Y, Evans A (2011) Downscaling climate change information: an essential ingredient to incorporate uncertainties into adaptation policies. In: Chan F, Marinova D, Anderssen RS (eds) MODSIM2011, 19th international congress on modelling and simulation. Modelling and Simulation Society of Australia and New Zealand, Canberra, p 1652–1658

Ummenhofer CC, England MH, McIntosh PC, Meyers GA and others (2009) What causes southeast Australia's worst droughts? Geophys Res Lett 36:L04706, doi:10.1029/2008GL036801

Whan KB, Timbal B, Lindsay J (2013) Linear and nonlinear statistical analysis of the impact of the sub-tropical ridge intensity and position on south-east Australian rainfall. Int J Climatol 34:326–342

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